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Eloctrostatic Pull-in Characteristic of Silicon Diaphragm for MEMS Micropump Design

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Abstract

Electrostatic actuation method is commonly employed for MEMS micropump mechanism which consists of diaphragm microstructure and parallel electrode. This work discussed on design and simulation of square silicon diaphragms and it characteristics for micropump application which supply voltage range of 0V-20V. The characterizations of these diaphragms were based on the measurement on parameters such as diaphragm displacement as function of voltage applied and stress distribution. The simulations were carried out using CoventorWare2007. Results show that simulation deviate theoretical value in a range of below 15 %. The displacement of the diaphragm was proportional to the physical geometry of the diaphragm. Pull-in voltage defines the limitation value for micropump operation.

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Keywords: MEMS; diaphragm; electrostatic pull-in.

1. Introduction

MEMS technology can be defined as the integration of mechanical element, sensors, actuators and electronics on a common silicon substrate through microfabrication technology. Diaphragm plays a major role in MEMS actuators because of efficient in volume displacement, offer large area bending and is easy to fabricate using lithography techniques. Diaphragm can be deflected in a controlled manner using various transducer techniques, such as electrostatic [1], electromagnetic [2], piezoelectric [3] and thermo-pneumatic actuation [4]. Square shape silicon based diaphragm has been used intensively for development of MEMS particularly for pressure sensors [5] and micropumps [6].

The majority of micropumps are reciprocating displacement pumps in which the moving surface is a diaphragm [6]. These are commonly called as membrane pumps or diaphragm pumps. Electrostatic actuation plays an important role in realization of MEMS micropump. It can be modelled as a parallel capacitance plats together with mass-spring system to observe the displacement or deflection of the diaphragm. The main parameters need to be taken into consideration are electrostatic stability or pull-in effect [7] and voltage supply range.

This work was done to characterize the electrostatic pull-in of silicon square shape diaphragm for micropump design. Simulations were carried out using CoventorWare2007. The characterization of the structure will be defined in term of

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parameters such as displacement, pull-in voltage and von misses stress distribution. Parameters for physical design consist of diaphragm dimension, electrode gap and Young's modulus. The load range is 0 V-20 V and displacement limitation is 1 µm. Simulation results in term of diaphragm displacement were obtained and compared with the calculation values to observe the deviation percentage.

2. Working Principles

Two parallel plates with gap (*d*), given an applied voltage (*V*) and capacitance (*C*) between the plates as shown in Figure 1, generate an electrostatic force between the two plates, can be calculated by taking the derivative of the energy in the direction of motion. Hence for *x* direction, the electrostatic force is given by [7]:

$$F_{e,x} = \frac{\partial W_e}{\partial x} = \varepsilon_0 \frac{AV^2}{2d^2} \tag{1}$$

In equilibrium, a linear relationship which the mechanical restoring force, F_m from the mass-spring system is related to it displacement *Z*, by the following equation:

$$Fm = -K_Z Z \tag{2}$$

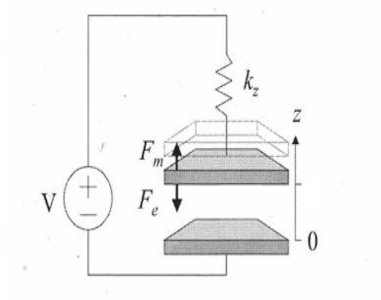


Fig. 1. Net proofmass displacement of varying V_t as a function of g.

The mechanical stiffness of the spring in the z direction, K_z can be calculated by [8]:

$$K_Z = \frac{Et^3}{\alpha L^3} \tag{3}$$

The force balance equation for this model can be derived by summing together the actuating nonlinear electrostatic force, F_e and the linear restoring force due to the mass-spring system, F_m, thus $F_e + F_m = 0$. Hence the equation can be written as:

$$\frac{1}{2}\frac{\varepsilon A}{d^2}V^2 + \left(-K_Z Z\right) = 0 \tag{4}$$

$$\frac{1}{2}\frac{\varepsilon A}{d^2}V^2 = K_Z Z \tag{5}$$

The minimum voltage to electrostatically pull-in or snap-through a membrane can be determined from equilibrium of electrostatic and thin plate spring forces (F_e+F_m). Thus, the pull-in voltage for a capacitor with two dielectric layers is given by [1]:

$$Vpull\_in = \sqrt{\frac{8K_z d^3}{27\varepsilon A}} \quad (6)$$

One major problem with electrostatic forces is that they are always attractive and nonlinear because they are proportional to the voltage squared and inversely proportional to the gap squared. Thus pull in voltage determines the maximum value of voltage supply range.

3. Results and Discussions

3.1 Diaphragm Displacement Distribution

MEMS square diaphragm microstructure with thickness of 15 μm, 25 μm and 35 μm, and the side length of 2000 μm, 3000 μm, and 4000 μm were designed with two sets of electrode gap values, 1 μm and 4 μm respectively. The Young's modulus and Poisson Ratio for silicon were fixed to 150 GPa and 0.30 respectively. Finite element model with refined Manhanttan meshing technique was used. In this design, yield stress of silicon is 2.8 GPa-6.8 GPa for von misses stress criterion.

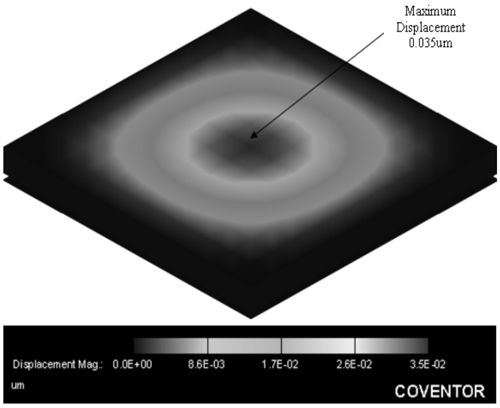


Fig. 2. Cross-sectional view of diaphragm displacement distribution with applied 12 V.

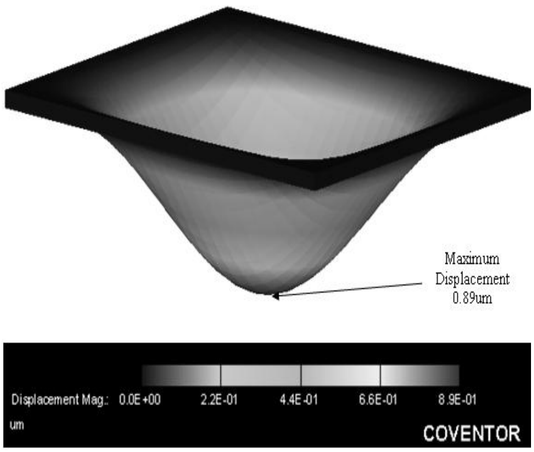


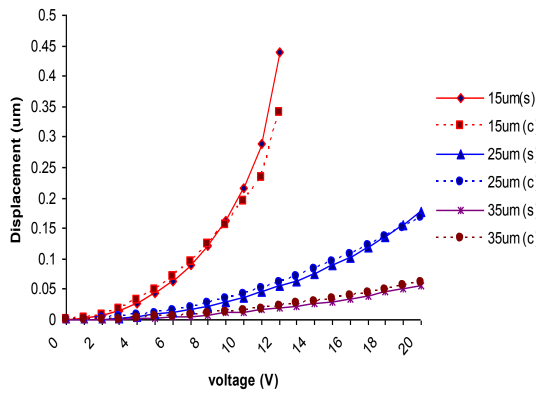
Fig. 3. Visualization of diaphragm displacement with applied 20 V.

Boundary condition (BE) was applied to the diaphragm which all four sides remain fixed. The diaphragm itself as ground element while the parallel plate was loaded with distributed supply voltage. Based on Figure 1, it was obviously shown the displacement distribution which the center part of the diaphragm experienced the maximum deflection.

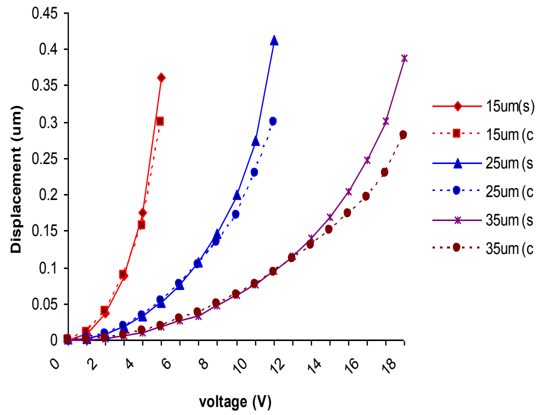
Figure 2 shows the visualization of diaphragm displacement with applied 20 V. The 2000 μm diaphragm and electrode gap of 4 μm gives the diaphragm maximum displacement of 0.89 μm, which deviates the calculation value of 0.78 μm by 14%.

Simulation results were shown in Figure 3 and Figure 4 respectively for 1 μm and 4 μm electrode gap which the dashed line refer to the theoritical value. It was clearly shown that diaphragm with thickness decreased will results of less pull-in voltage value and electrostatic stability range. For instance, based on Figure 2(b), operation range for diaphragm with 15 μm thickness was 0 V- 5 V, while for 25 μm the range increased by more than 100% which from 0 V – 11 V, and for 35 μm, the operation range also increased almost by 100%, from 0 V –19 V. Based on Figure 2, an increasing in diaphragm square dimension from 2000 μm to 4000 μm, decreased the operation voltage range, thus the pull-in voltage value would decreased as well.

In order to have a wider electrostatic stability range or voltage operation, the electrode gap need to be increased. Figure 3 shows the simulation results which all the designs could be operated until 20 V. Comparison that had been made to the simulation results shows that simulation deviate theoretical value in the range of 0.5% - 15%. Smaller deviation value can be obtained if more meshing refinement is applied but consume more time for simulation.



(a)



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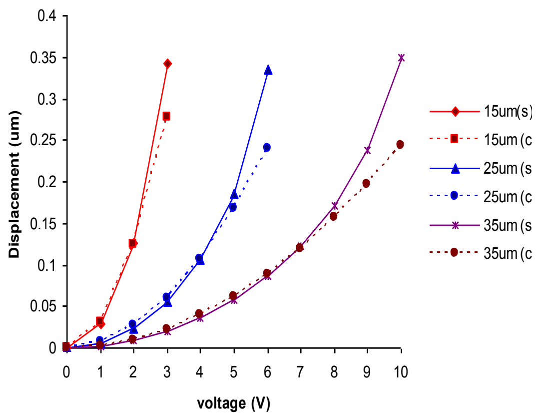

(c)

Fig. 4. Diaphragm displacement as function of voltage applied for 1 μm electrode gap with diaphragm dimensions of (a) 2000 μm, (b) 3000 μm, and (c) 4000 μm.

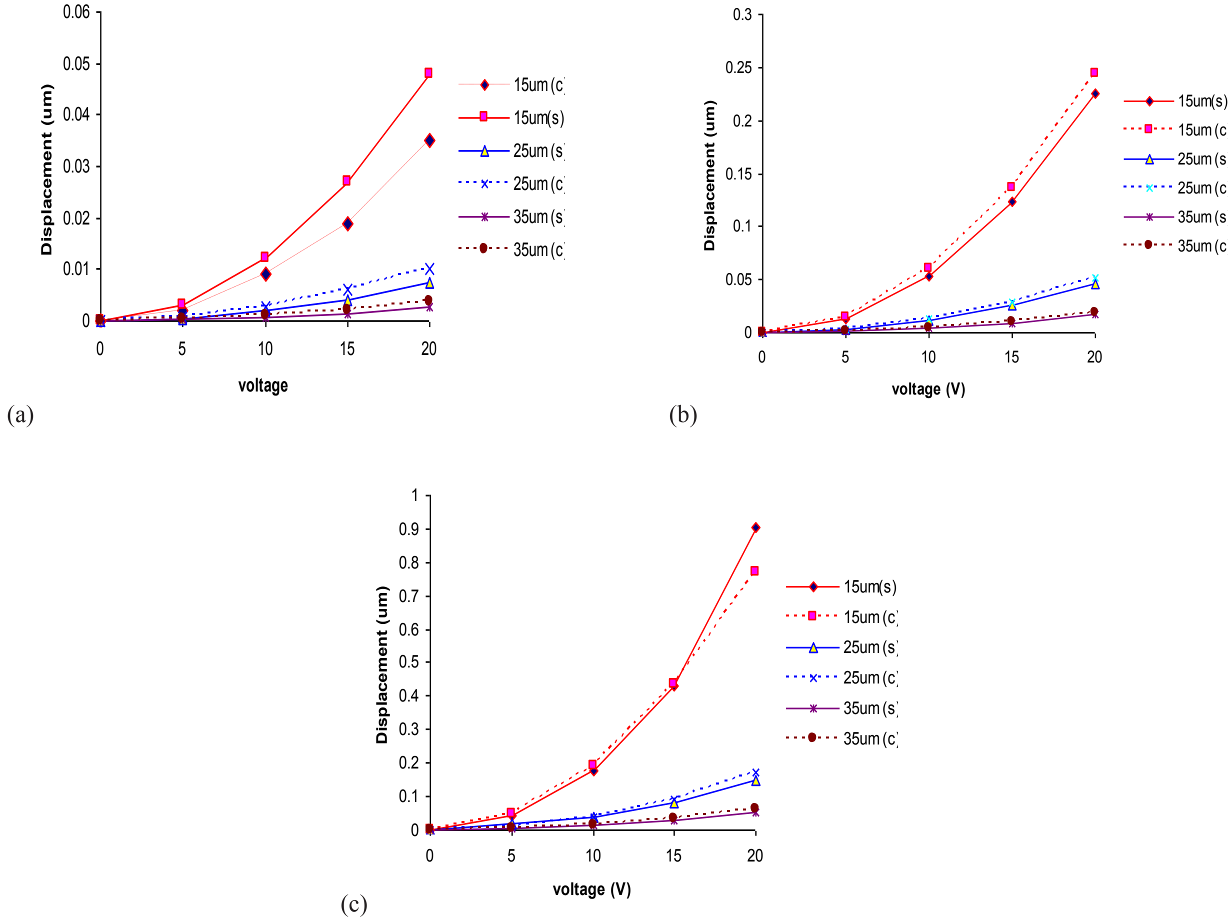

Fig. 5. Diaphragm displacement as function of voltage applied for 4 μm electrode gap with diaphragm dimensions of (a) 2000 μm, (b) 3000 μm, and (c) 4000 μm.

3.2 Von Misses Stress Distribution

The failure criterion states that von misses stress should be less than the yield stress of the material [9]. It also determines the diaphragm survivability under extreme loading condition. The maximum value of von misses stress distribution occurred at the edge of the diaphragm fixed part as shown in Figure 5 which is 0.3 Mpa, loaded with 12 V for design dimension of 2000 μm, 15 μm thickness and 4 μm electrode gap.

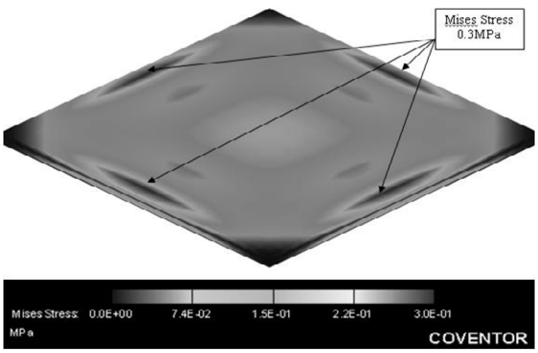

Fig. 6. Cross-sectional view of diaphragm von mises stress with voltage applied.

Figure 6 shows the von misses stress distribution as function of diaphragm square size with 4 μm of electrode gap. The plotting values were defined by the highest point of the displacement for each design. An increment in displacement and voltage applied increased the value of von misses stress distribution at the diaphragm fixed end. A higher value of the stress in the structure may result to failure of the structure if the stress reaches it critical value known as yield strength.

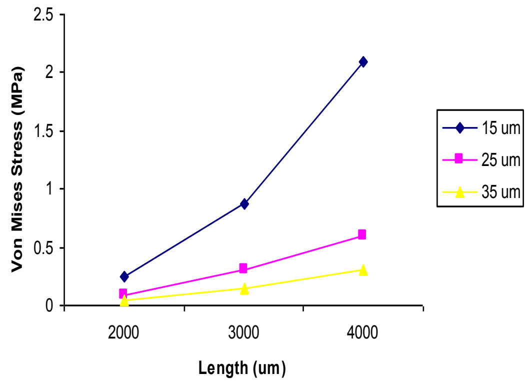

Fig. 7. Characterization of von misses stress as function of diaphragm dimensions

4. Conclusion

The electrostatic pull-in characteristics of square silicon diaphragm microstructure designs were presented. By using simple plate diaphragm theory with electrostatic force balanced, the displacement of the MEMS diaphragm microstructure was observed. From the result, the displacement of diaphragm was depending on electrostatic stability range or voltage value. By increasing the diaphragm thickness or electrode gap, the operating voltage range could be increased. Simulation results deviate the theoretical value in the range of 0.5% - 15%. The von misses stress shows its concentrated at the middle of the diaphragm edge. The stress criterion predicts the yielding of material and fatigue failure and shows the microstructure survivability.

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